Large-Eddy Simulations of Mixing due to Solitary Waves, with Application to the CMO Experiment

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LONG-TERM GOALS

My long-term goal is to develop a facility for the efficient numerical modeling of waves and turbulence in the coastal oceans. The ultimate result will be improved methods for the parameterization of small-scale, coastal mixing processes (particularly sediment resuspension) in mesoscale models.

OBJECTIVES

During the Coastal Mixing and Optics (CMO) experiment, intensive measurements of internal waves and mixing events were obtained at a location on the continental shelf south of Martha's Vineyard. Intense mixing was observed, due both to the effects of local surface forcing and to the effects of remotely-generated nonlinear internal waves. The passage of Hurricane Edouard in September of 1996 caused dramatic changes in the vertical structure of the water column. Not only did the hurricane mix the ocean directly, it changed the nature of ongoing mixing processes that depend on background stratification, such as tide-generated solitons.

This report describes a program of small-scale numerical modeling designed to clarify the mixing properties of solitary waves in a coastal environment, with particular reference to the change in water column dynamics brought on by the hurricane.

APPROACH

An LES model of coastal solitons has been developed, tested and optimized on OSU's Connection Machine CM500e. The first challenge was to initialize the model so as to produce a realistic solitary wave. It is not possible to include the generation process in the model; instead the model is initialized with a solitary wave solution of the Korteweg-deVries (KdV) equation, modified to include a bottom boundary layer. This waveform differs from observed coastal solitons in several important respects. First, it is an asymptotic solution of the Navier-Stokes equations which assumes inviscid flow and a small-amplitude, long-wavelength disturbance. Nevertheless, this modified KdV soliton is the best available model for the observed solitary waves.

The next step was to include a representation of sediment resuspension. Sediment is modeled as a continuous concentration field, with weak diffusivity and a realistic settling velocity. Sediment is introduced into the flow via a bottom flux parameterization. The structure function formulation (e.g. Skyllingstad et al. 1999) provides the basis for an effective parameterization of subgrid scale fluxes.

Particular attention is paid to the treatment of the bottom boundary layer, in order to ensure accurate representation of resuspension physics.

The plan has been to simulate two cases: one in which the stratification is restricted to the upper half of the water column, and one in which only the lower half is stratified. These correspond to conditions occurring before and after the passage of Hurricane Edouard.

WORK COMPLETED

Model development, testing and optimization are complete. Both direct and large-eddy simulations have been conducted and the results analyzed.

RESULTS

Figure 1 shows results from a sample simulation of the post-hurricane case, i.e. that in which the lower part of the water column is stratified. As I hoped, the KdV initialization produces a stable solitary wave with propagation characteristics similar to those observed in both laboratory and observational studies. Except near the bottom, the simulated flow field is laminar, and mixing processes are correspondingly weak.

The most important aspect of this flow for sediment resuspension is the bottom stress. The model was initialized with a weak viscous boundary layer at the bottom which has been intensified over time by the wave-induced flow. The stress increases correspondingly, so that the flow develops strong potential for scouring sediments from the bottom. In the present flow, however, vertical transport of sediments is very weak due to the absence of turbulent mixing.

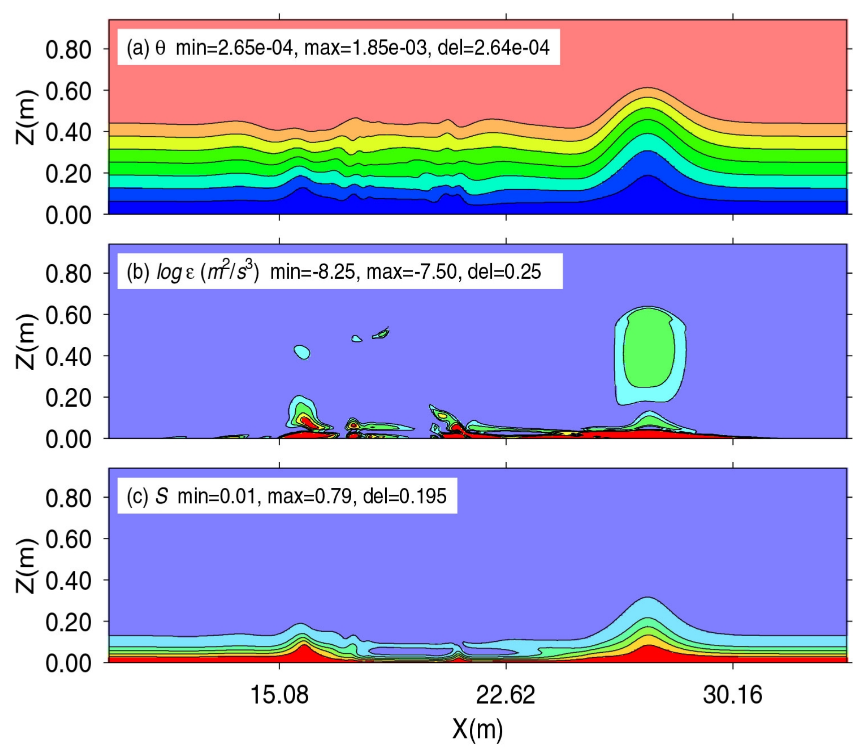


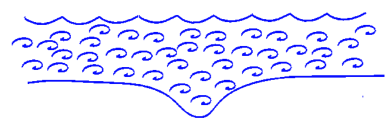
Figure 1: Cross-section of a simulated solitary wave, showing temperature, TKE dissipation rate and sediment concentration.

The absence of interior mixing was contrary to my expectations. Over a wide range of parameter values, solitons were found to remain laminar except in the bottom boundary layer, i.e. the expected mixing in the soliton interior did not develop. In LES runs at high Reynolds number, mixing was generated entirely by the subgrid-scale model and thus cannot be regarded as realistic. It must be concluded that turbulent mixing does not occur in this simple model of coastal soliton propagation. Further study of mixing due to coastal solitons will require incorporation of additional physical effects.

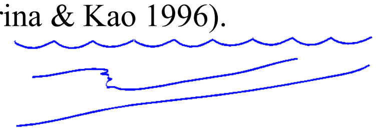
IMPACT/APPLICATIONS

Mixing by solitons is something of a contradiction. Solitons are distinguished by their extreme stability, and are able to propagate over long distances in part because they are essentially non-dissipative. (The balance between nonlinearity and dispersion prevents the cascade of energy to dissipation scales.) The simulations of coastal solitons described above have shown that these structures have very little tendency to mix. I now consider five possible modifications to the classical soliton model employed so far in this study that might account for observations of mixing in association with ISW passage.

(1) *Illusory Mixing*
Pre-existing turbulence, e.g. from a mixed layer, is advected through the structure of a soliton. In this case, the soliton plays no role in generating turbulence.



(2) *Shoaling*
As a soliton propagates into shallow water, it attempts to adjust to the evolving dispersion relation by losing energy to dissipation. This mechanism is thought to play a central role in the evolution of coastal solitons. It has been studied theoretically, both via modifications to the Korteweg-DeVries equation and via explicit, two-dimensional simulations (e.g. Saffarina & Kao 1996).



(3) *Interaction with the Bottom Boundary Layer*
The soliton may set up a strong bottom boundary layer, with flow separation and adverse pressure gradient resulting in an inflectional velocity profile. The result may be a global (or absolute) instability, which leads to intense mixing. Since the main structure of the soliton is not necessarily involved in mixing, energy loss could be quite slow, while still generating intense turbulence in a thin layer. This mechanism could be important for sediment resuspension in coastal regions (Bogucki *et al*. 1997, Redekopp 1999).

(4) Mixing by Soliton Shear
Velocity shears within the soliton could lead to low gradient Richardson number and dynamic instability. Many authors (e.g. Sandstrom *et al*. 1989, Bogucki & Garrett 1993, Sandstrom & Oakey 1995) have discussed versions of this mechanism. In this scenario, soliton longevity is limited by the loss of energy to turbulence.

(5) *Interaction with Ambient Shear*
Suppose that a soliton propagates in a sheared environment with gradient Richardson number not much larger than ¼. The soliton may cause a local decrease of the gradient Richardson number via both shear amplification and straining of isopycnals. Because the background shear would provide an energy source for turbulence, the soliton might propagate over a long distance, causing extensive modification of the background flow.

Mechanisms (2), (3) and (5) are most likely to be important in the context of coastal mixing. Shoaling (2) is has been studied extensively since the early eighties and is now relatively well understood. The potential importance of bottom mixing (3) in CMO is under investigation by Redekopp and Bogucki. In contrast, interactions with ambient shear (5) remain almost entirely unexplored. Many authors (Lee & Beardsley 1974, Maslowe & Redekopp 1980, Tung *et al*. 1981, Gear & Grimshaw 1983) have discussed the weakly nonlinear theory for solitons in a sheared environment, but the difficulty of solving the resulting equations has hampered further investigation. Although vertical shear is ubiquitous in the ocean, soliton observations are invariably interpreted in terms of models that assume a motionless background state (e.g. Sandstrom & Oakey 1995). The potential for induced dynamic instability in a nearly critical background flow remains, to my knowledge, entirely unexplored.

Present results suggest that interaction with background shear may represent a key element in the mixing properties of the CMO solitons. Elucidation of that interaction will be essential to future progress, and represents the logical extension of the present work.

TRANSITIONS

I am in regular communication with M. Levine, T. Boyd and J. Barth, who are analyzing observational data from CMO, and with K. O'Driscoll, who is conducting analytical studies using a modified KdV equation. D. Bogucki is studying soliton dynamics on a more fundamental level, using a combination of DNS and analytical approaches, with particular attention paid to the bottom mixing mechanism (3). Dr. Bogucki's project and my own are closely complementary; it is possible that we will collaborate on future extensions of this research.

RELATED PROJECTS

A theoretical study of mixing processes due to soliton-shear interaction (mechanism 5, above) is in development.

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